26th International Symposium on Ballistics

An experimental and numerical study of ballistic impacts on a turbine casing material at varying temperatures

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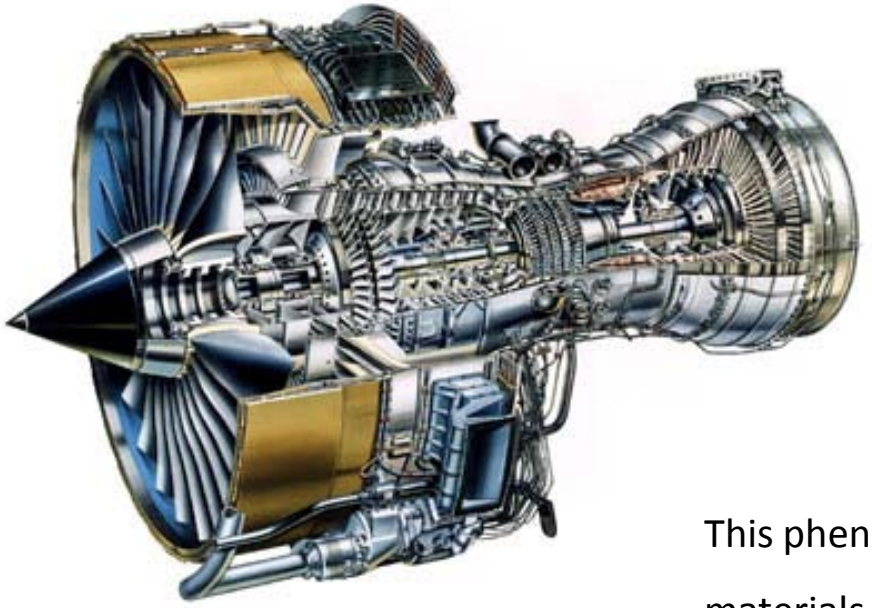
Motivation and objectives

- **Blade-off containment**
- If a turbine blade fails the case must contain all the fragments



Rotational velocity: 9,000 to 12,000 rpm

Diameter: Fan 2,5m Turbine: 1,2m

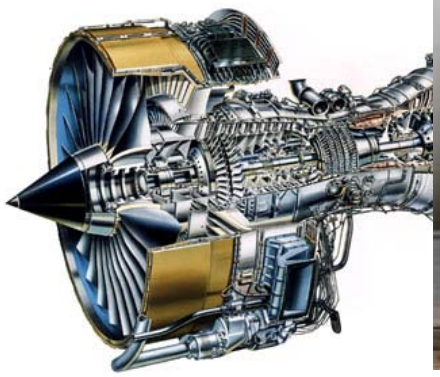
Temperature: 800ºC (blade) 500ºC (case)

This phenomenon is a High speed impact of materials operating at high temperature

Motivation and objectives

- Blade-off containment
- Mechanical behavior of FV535 steel

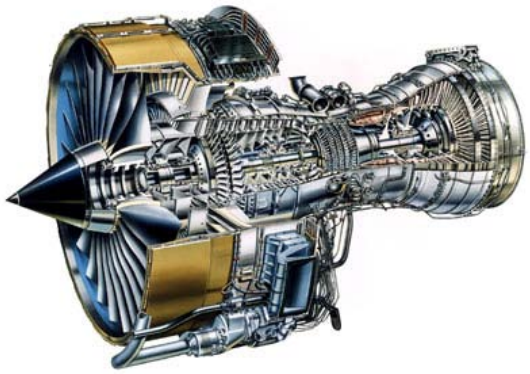
  at high temperature and high strain rate.



Motivation and objectives

- Blade-off containment
- Mechanical behavior of FV535 steel

  at high temperature and high strain rate.

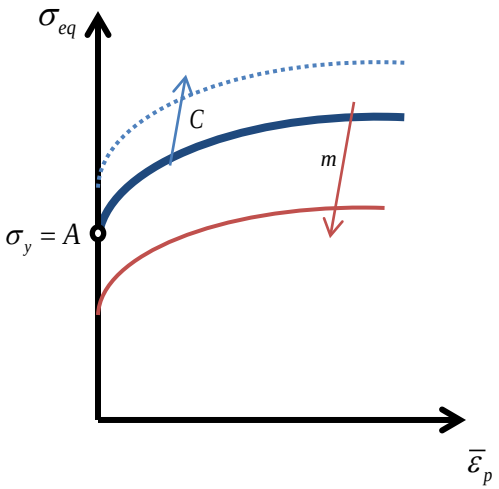


Motivation and objectives

- Blade-off containment
- Mechanical behavior case material at high temperature and high strain rate.
  - Case material: FV535, martensitic stainless steel 0.1%C 11%Cr
- Material modeling.
  - Static and dynamic tests to obtain material data at its operating conditions
  - Material model calibration.
    - Ballistics tests
    - Numerical simulations
- Numerical simulation of a blade-off event

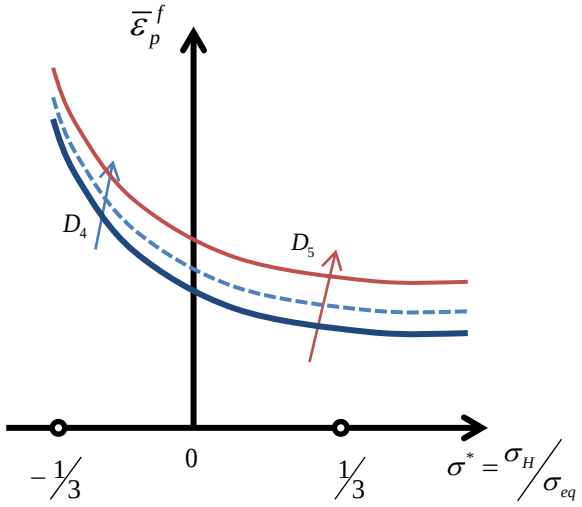
Contents

Johnson-Cook (JC) and Modified Johnson-Cook (MJC)



$$\sigma_{eq}^{JC} = \left[A + B\bar{\varepsilon}_p^{n}\right]\left[1 + C\ln\dot{\bar{\varepsilon}}_p^{*}\right]\left[1 - T^{*m}\right] \qquad \dot{\bar{\varepsilon}}_p^{*} = \frac{\dot{\bar{\varepsilon}}_p}{\dot{\varepsilon}_0}$$

$$\sigma_{eq}^{MJC} = \left[A + B\bar{\varepsilon}_p^{n}\right]\left[1 + \dot{\bar{\varepsilon}}_p^{*}\right]^{C}\left[1 - T^{*m}\right] \qquad T^{*} = \frac{T - T_r}{T_m - T_r}$$



$$\bar{\varepsilon}_p^{f\,JC} = \left[D_1 + D_2\exp\left(D_3\sigma^{*}\right)\right]\left[1 + D_4\ln\dot{\bar{\varepsilon}}_p^{*}\right]\left[1 + D_5T^{*}\right]$$

$$\bar{\varepsilon}_p^{f\,MJC} = \left[D_1 + D_2\exp\left(D_3\sigma^{*}\right)\right]\left[1 + \bar{\varepsilon}_p^{*}\right]^{D_4}\left[1 + D_5T^{*}\right]$$

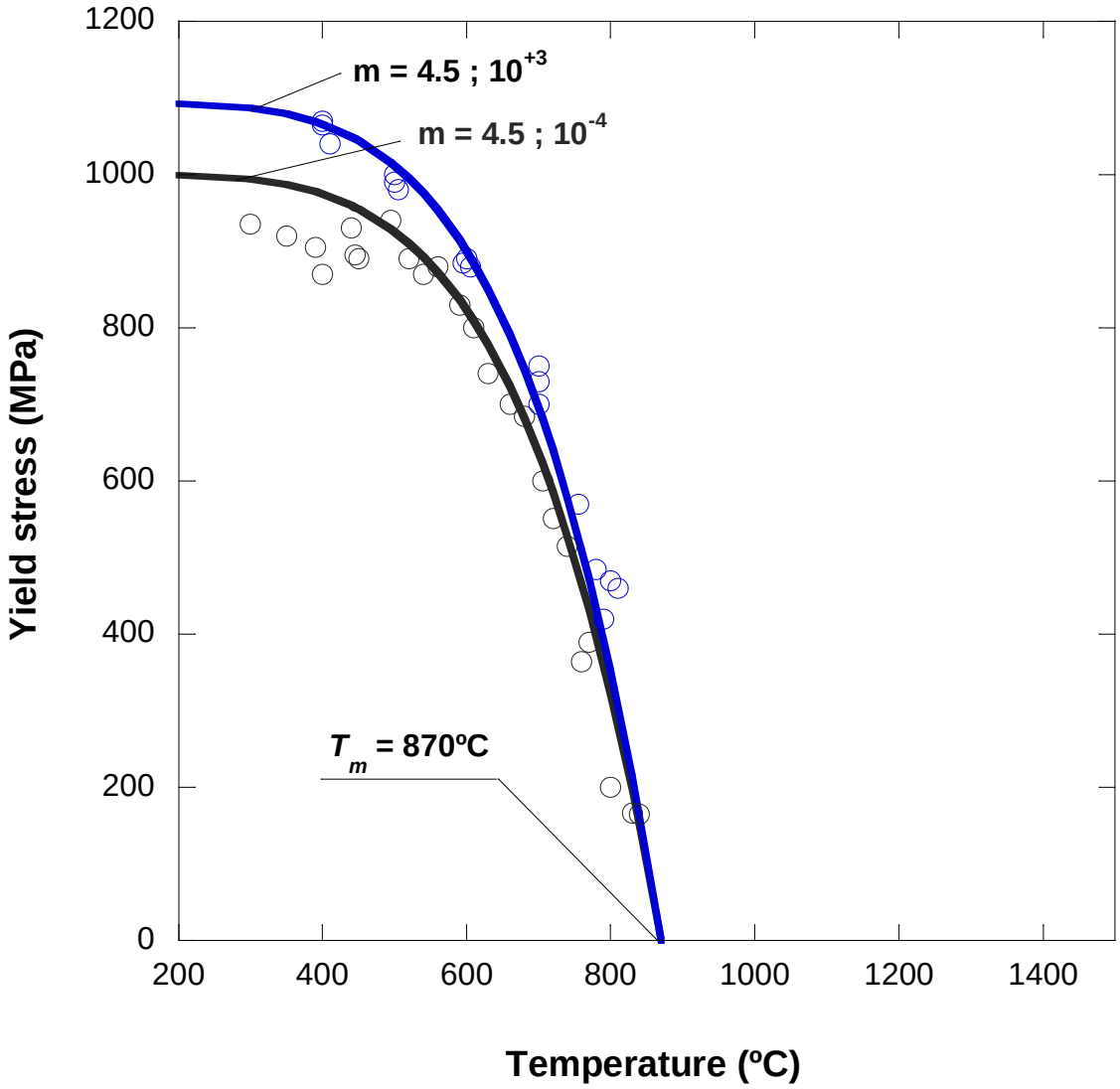
$$\dot{D} = \frac{1}{\bar{\varepsilon}_p^{f}}\dot{\bar{\varepsilon}}_p$$

Material testing

Low strain rate tests at 10^{-4} s^{-1} from T=24C to T=850C
Even up to 1200C

Hopkinson bar tests at 10^{3} s^{-1} from T=24C to T=850C

Material model



Thermal softening

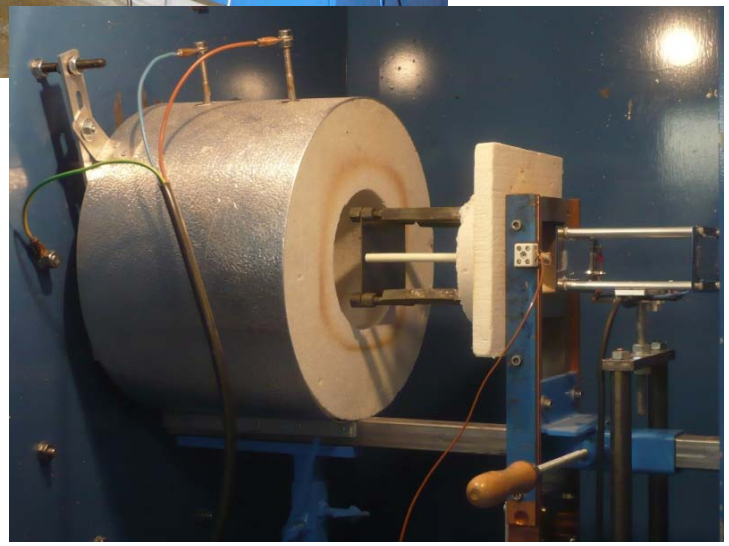
$$\sigma_{eq}^{JC} = A\left[1-\left(\frac{T-T_r}{T_m-T_r}\right)^m\right]$$

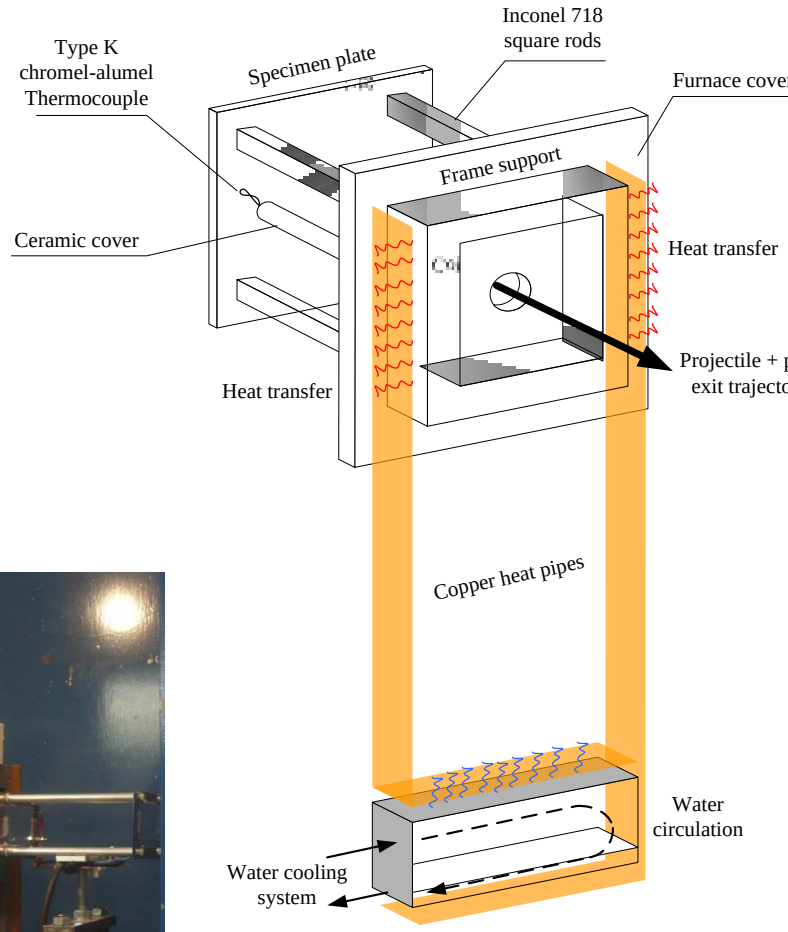
$$T_m = 870^{\circ}C$$

$$m = 4.5$$

Contents

Ballistic tests at high temperature

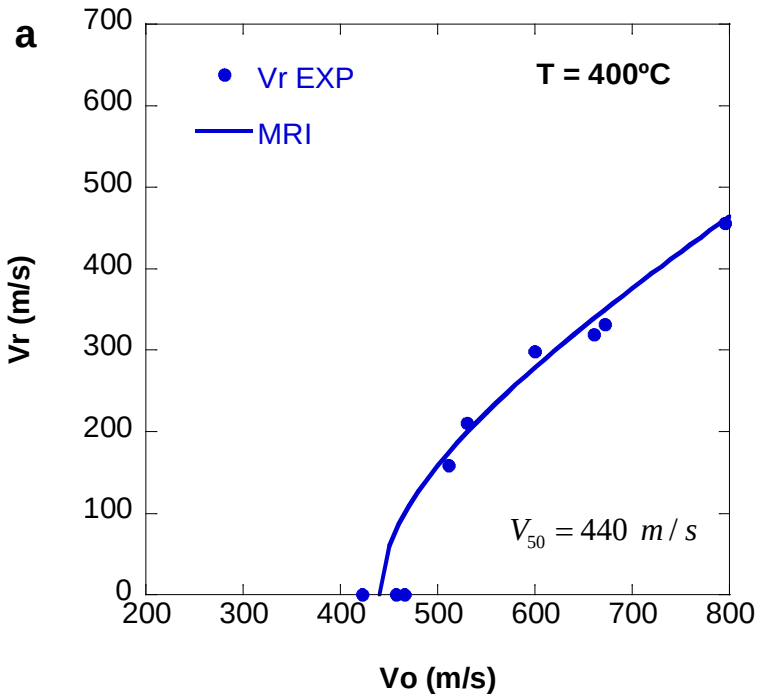


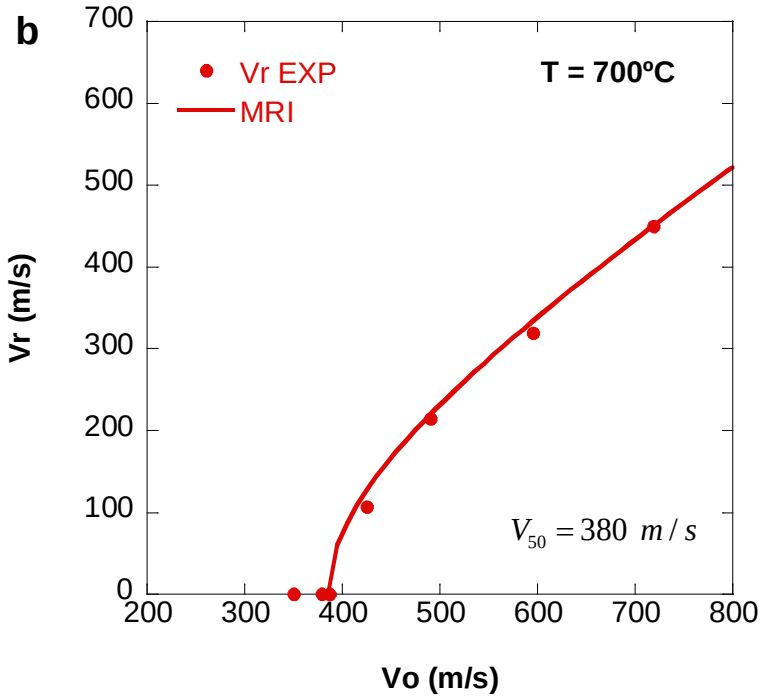


Samples:
Plates 100x100x1.6mm
400ºC and 700ºC

5.5mm ball

Ballistic tests at high temperature. Results





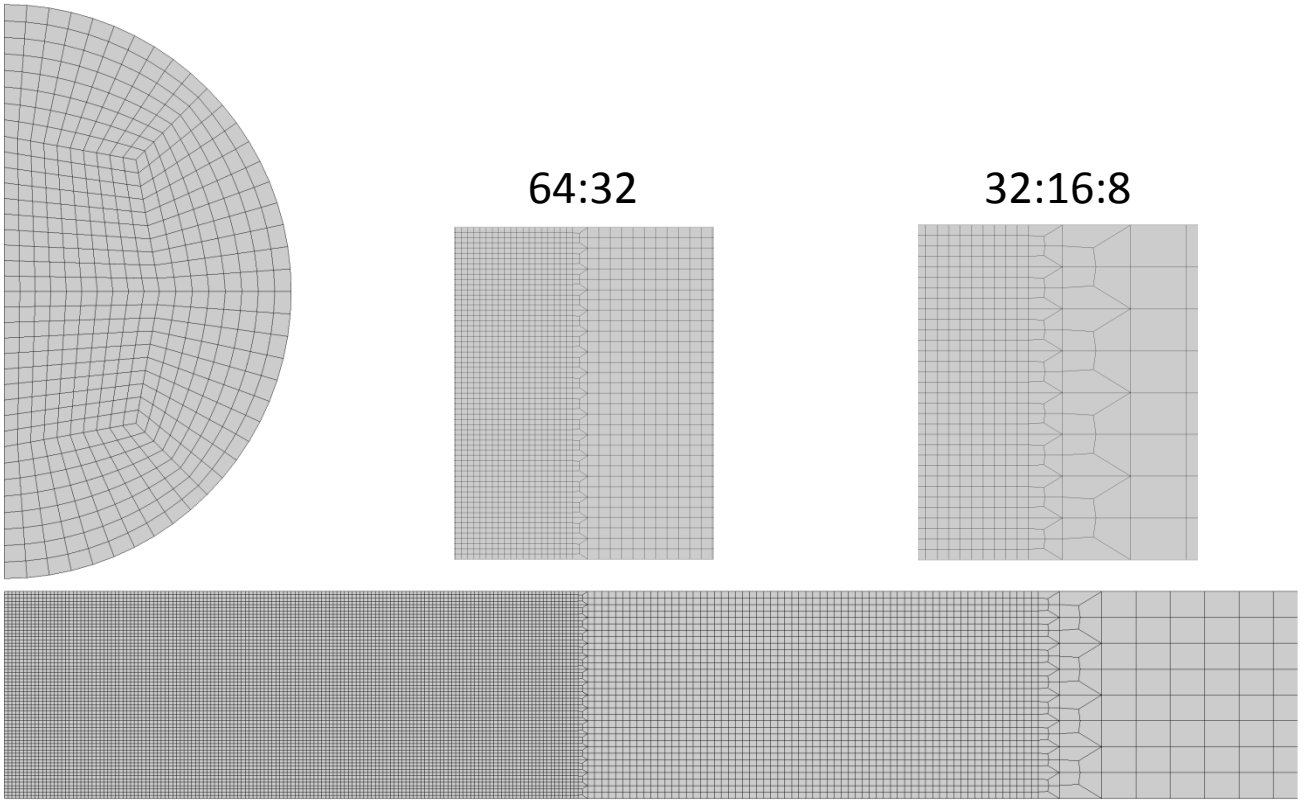
MRI (Modified Recht-Ipson)

$$v_r = \frac{k_1\left(v_0^{k_2} - v_{bl}^{k_2}\right)^{1/k_2}}{1 + m_p/M}$$

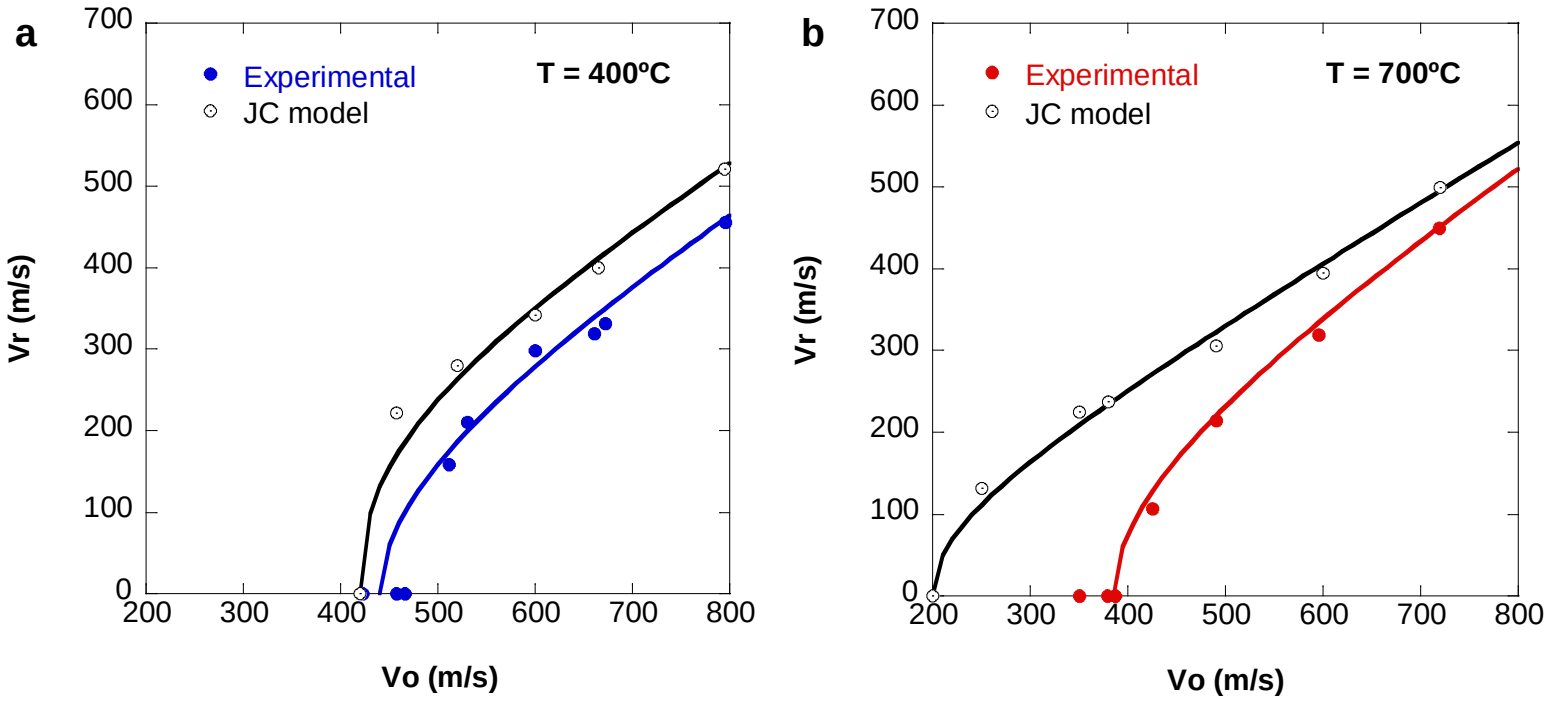
Contents

Numerical Simulations

- LS-DYNA, axilsimetric 2D.



Numerical Simulations: Results using JC model



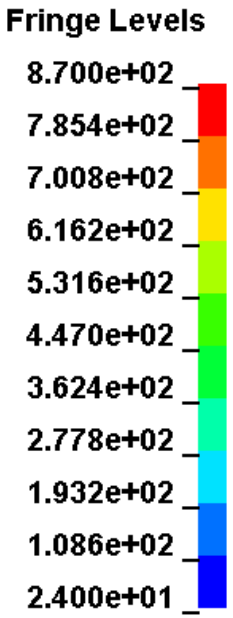
Numerical Simulations: Results using JC model

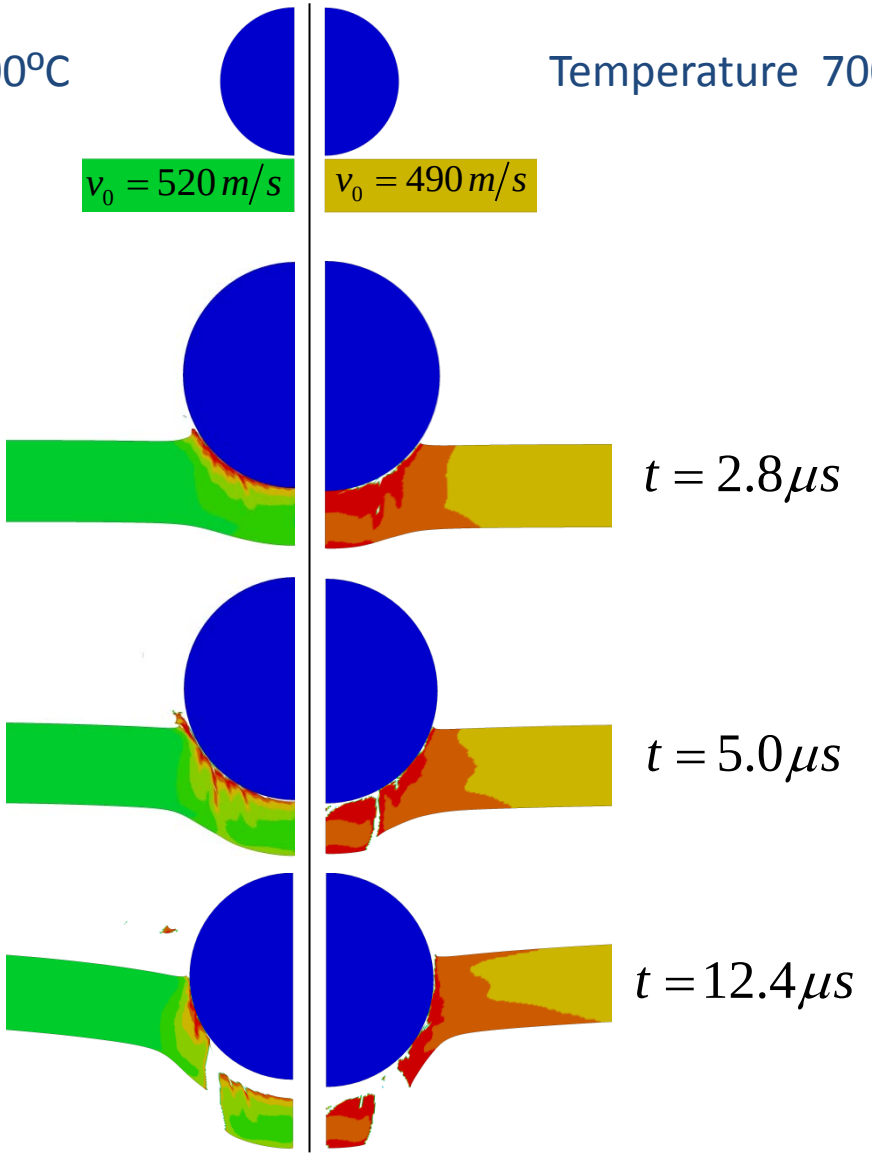
Temperature 400ºC

Temperature 700ºC

$v_0 = 520\,m/s$

$v_0 = 490\,m/s$





$t = 2.8\mu s$

$t = 5.0\mu s$

$t = 12.4\mu s$

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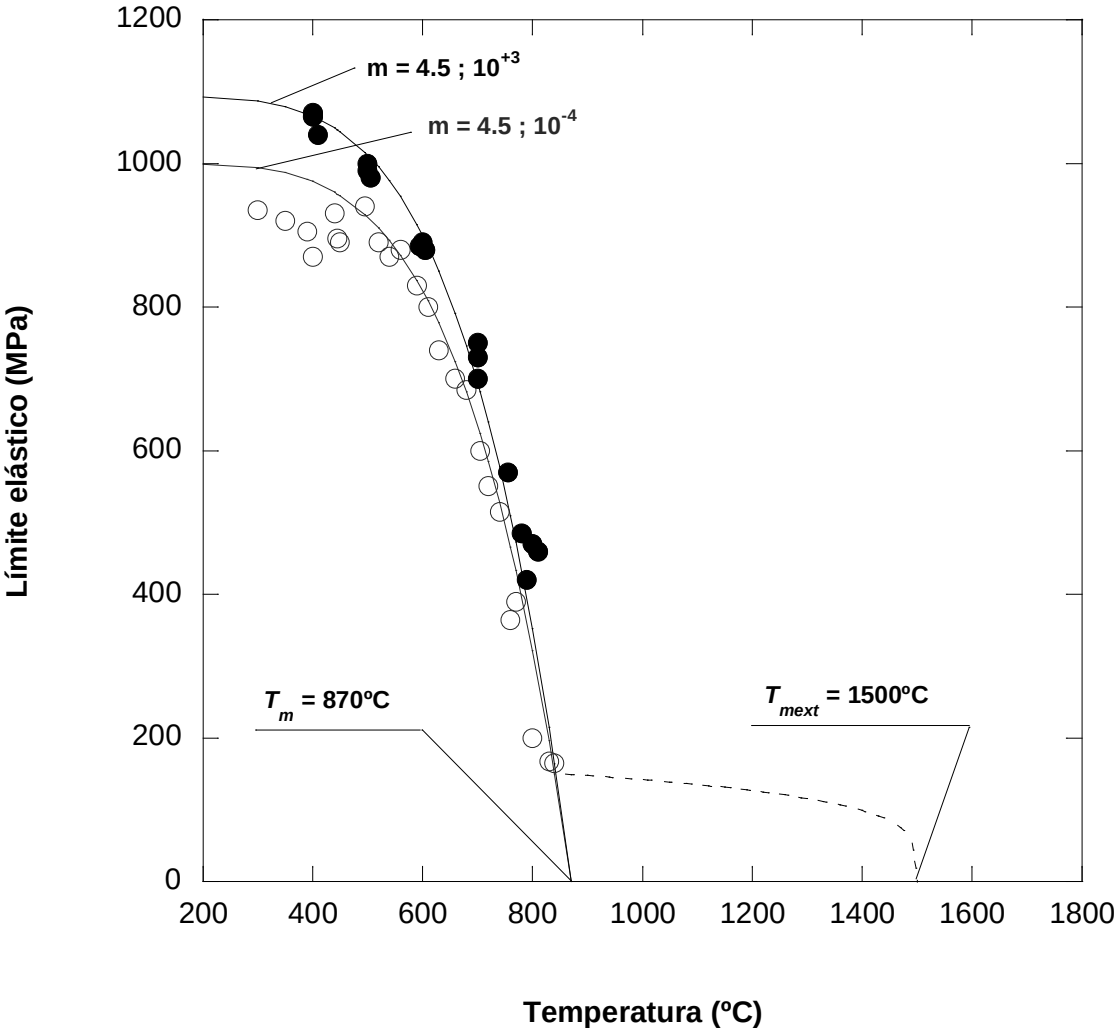
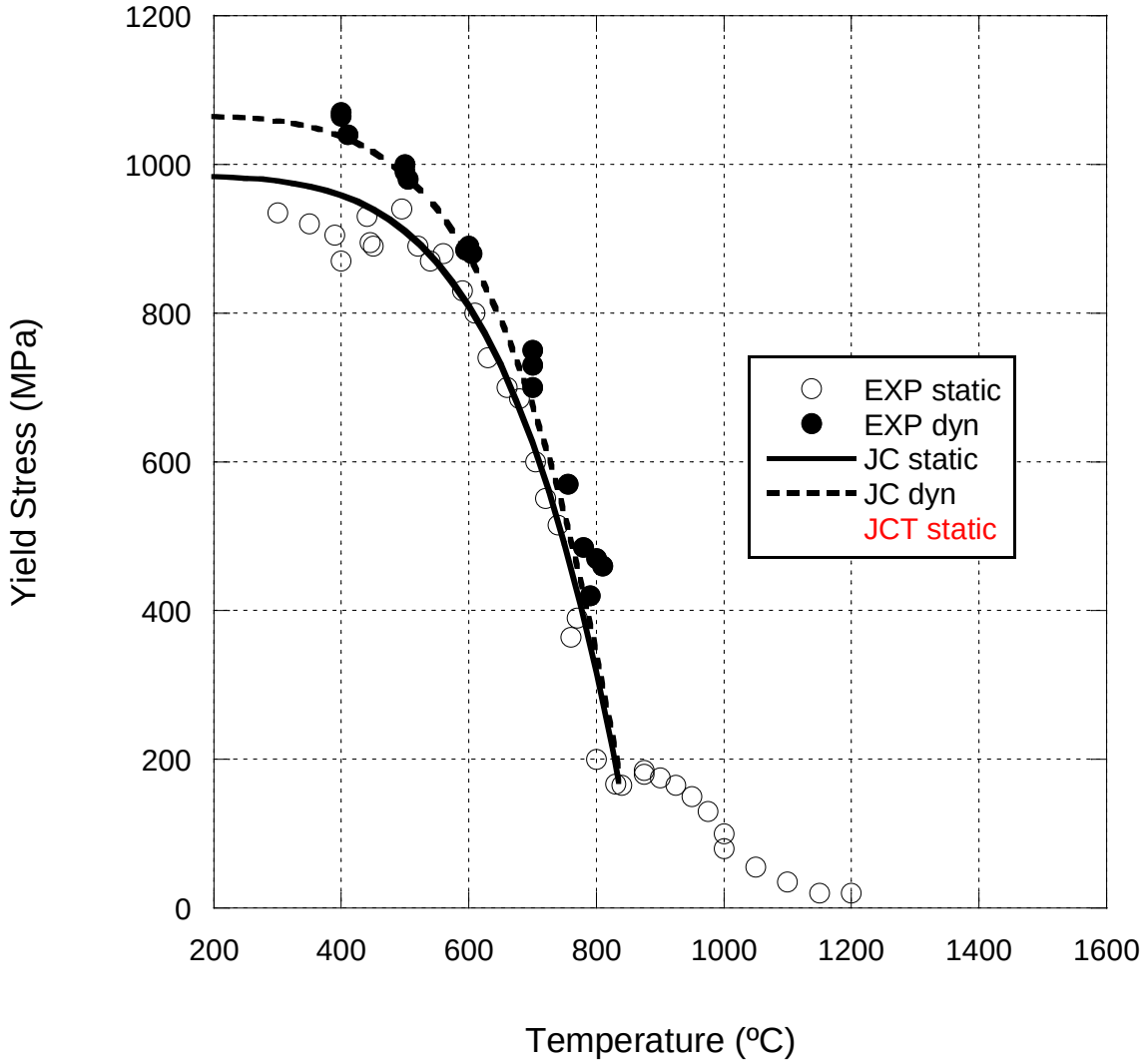
Modification of JC model: Melt extended temperature (JCT)



Modification of JC model: Melt extended temperature (JCT)



Modification of JC model: Melt extended temperature (JCT)

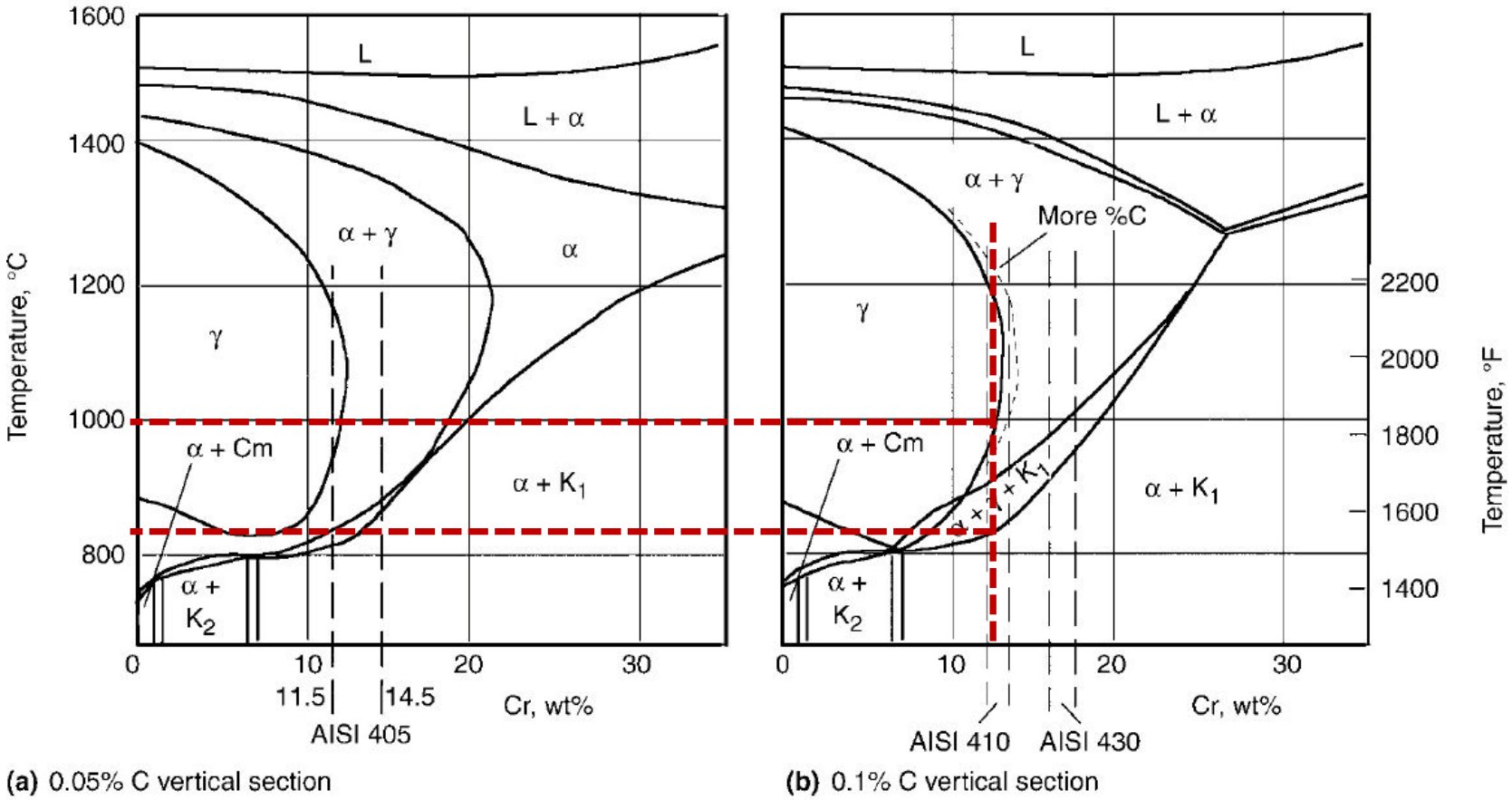


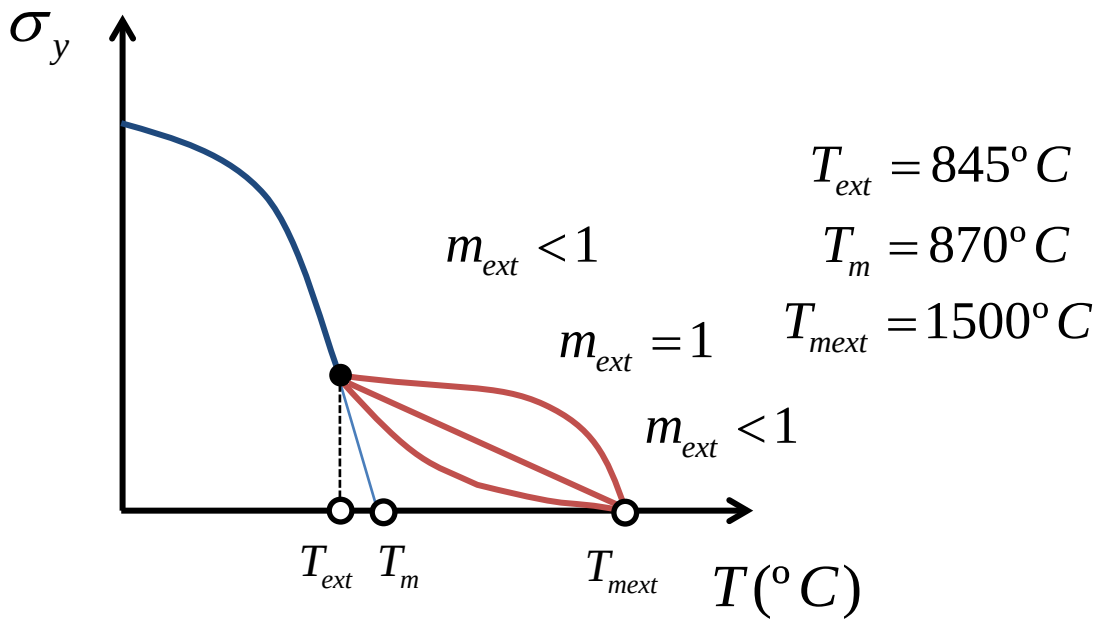
Fig. 13.4 Chromium-iron vertical sections of Cr-Fe-C ternary phase diagram at wt%C values of (a) 0.05 and (b) 0.1. Source: Ref 13.5, p 9-6. Copyright: 1958 Verlag Stahleisen GmbH, Düsseldorf, Germany

Modification of JC model: Melt extended temperature (JCT)

- Se propone la reformulación de la relación constitutiva:

$$\sigma_{eq}^{JC} = \left[A + B\bar{\varepsilon}_p^{n} \right]\left[1 + C \ln \dot{\bar{\varepsilon}}_p^{*} \right]\left[1 - T^{*m} \right]$$

$$\sigma_{eq}^{JCT} = \begin{cases} \sigma_{eq}^{JC} & T_0 \le T < T_{ext} \\ \sigma_{eq\ (T=T_{ext})}^{JC} \cdot T_{ext}^{*} & T_{ext} \le T \le T_{mext} \end{cases} \qquad T_{ext}^{*} = \left(1 - \frac{T - T_{ext}}{T_{mext} - T_{ext}} \right)^{m_{ext}}$$



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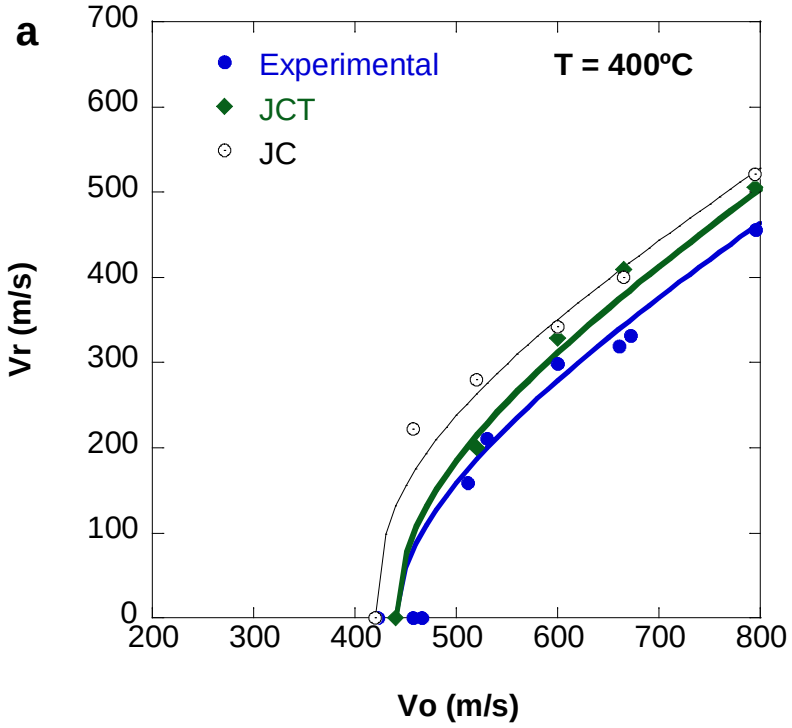
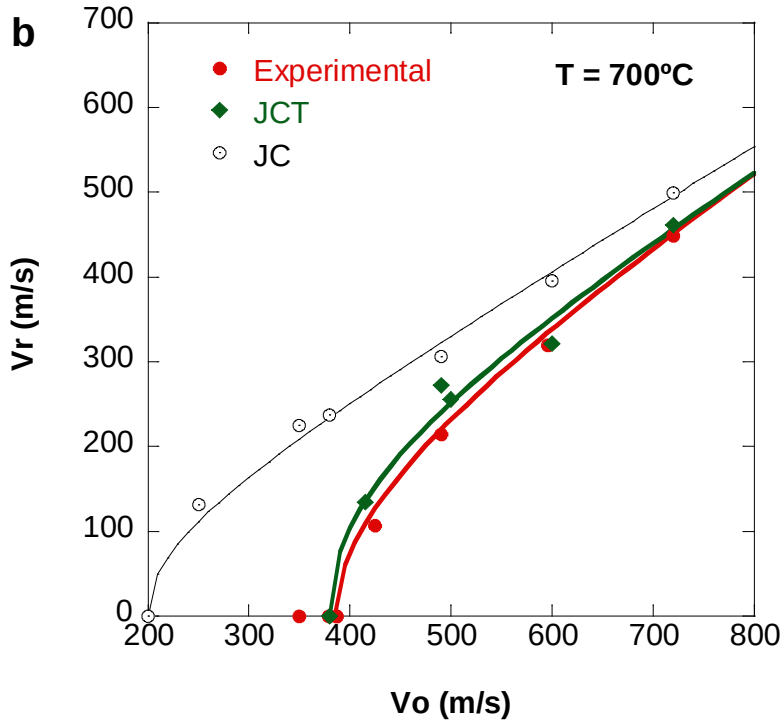
Numerical Simulations: Results using JCT model





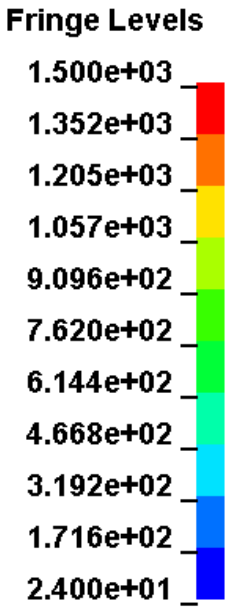
Numerical Simulations: Results using JCT model

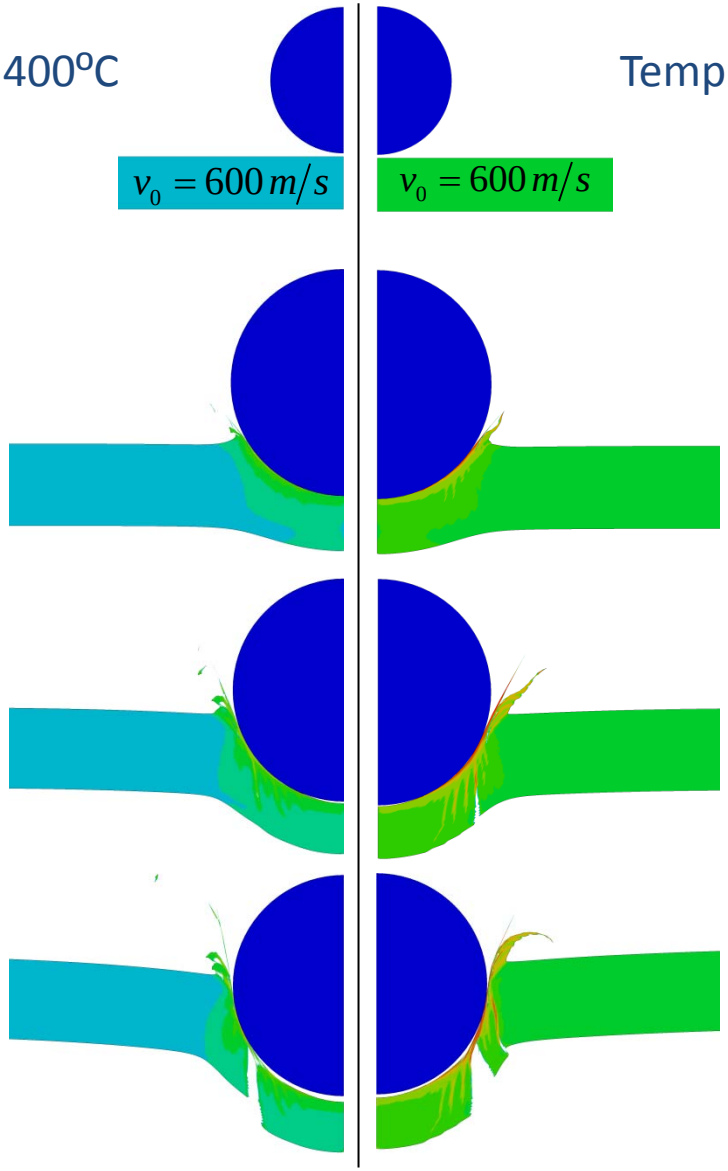
Temperature 400ºC

Temperature 700ºC

$v_0 = 600\,m/s$

$v_0 = 600\,m/s$





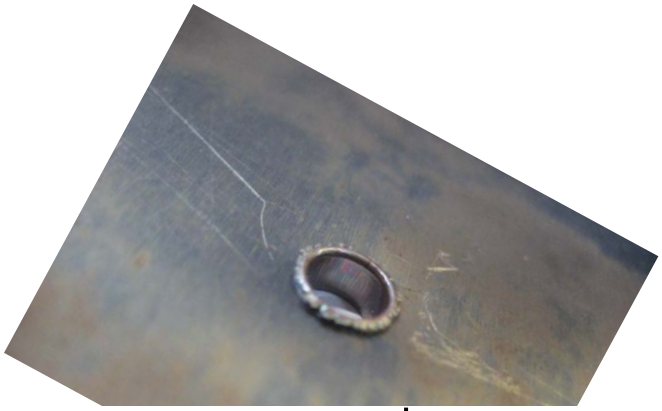
$t = 2.4\mu s$

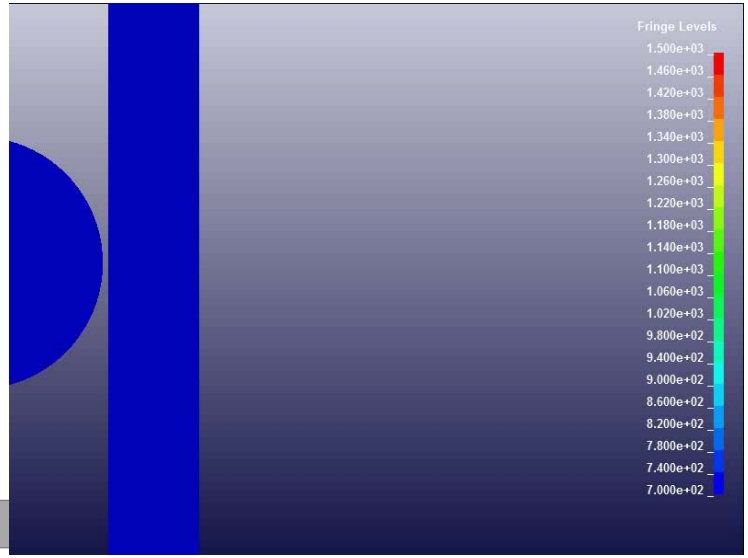
$t = 5.2\mu s$

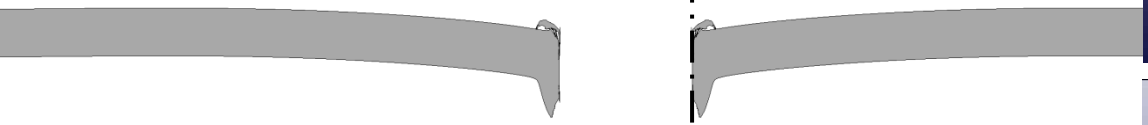
$t = 9.0\mu s$

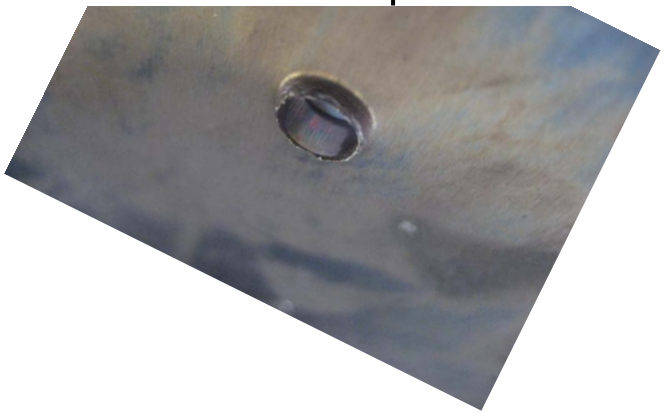
Numerical Simulations: Results using JCT model

700ºC
600m/s

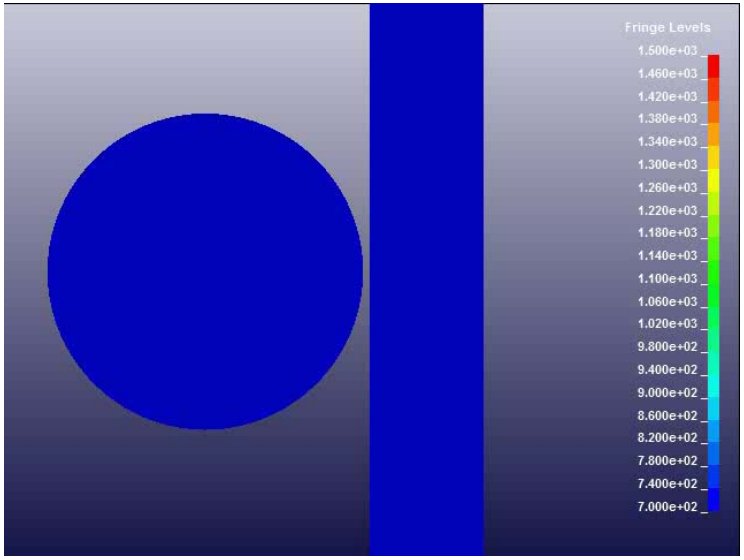








700ºC
380m/s



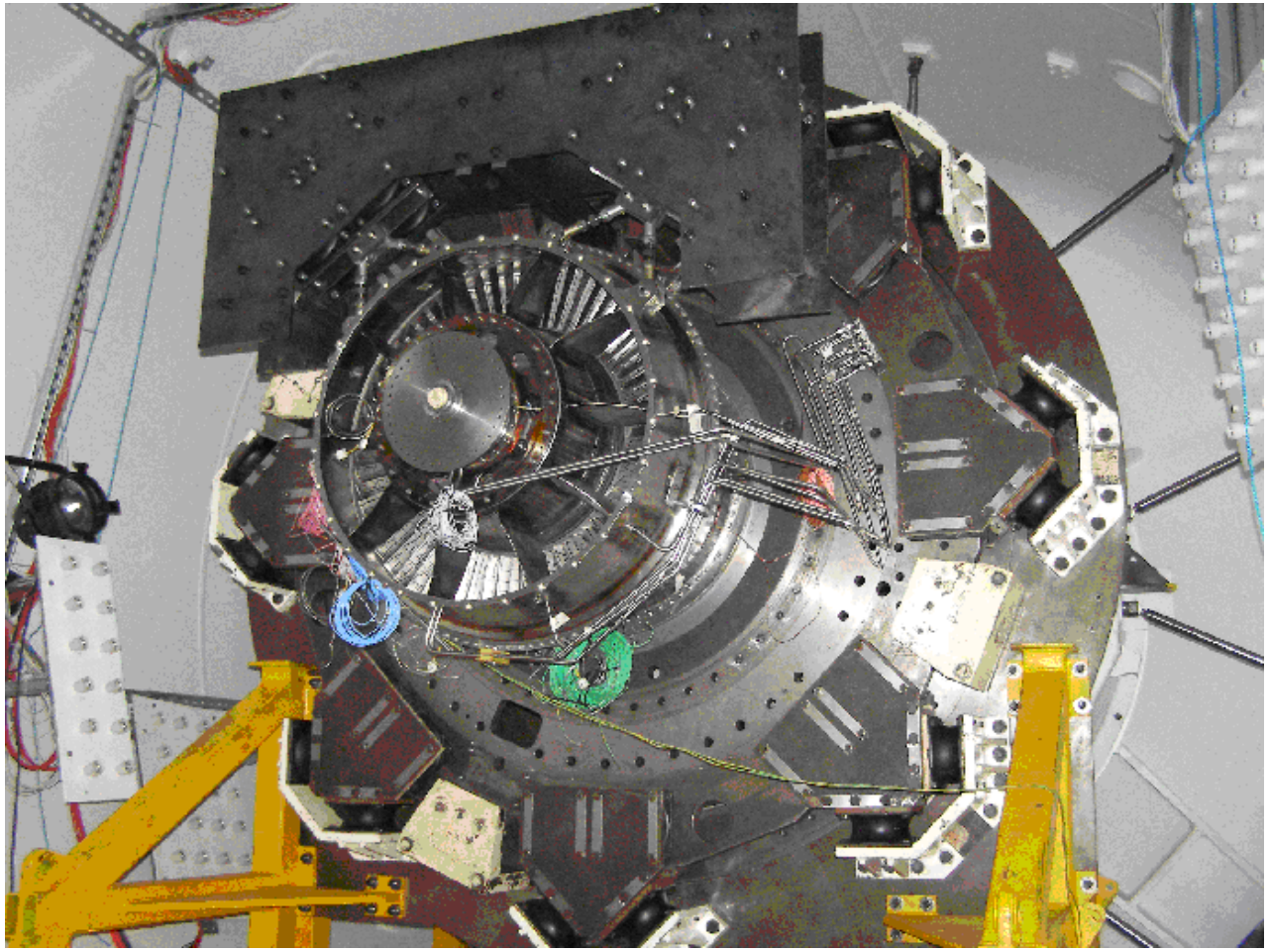
Contents

Conclusions

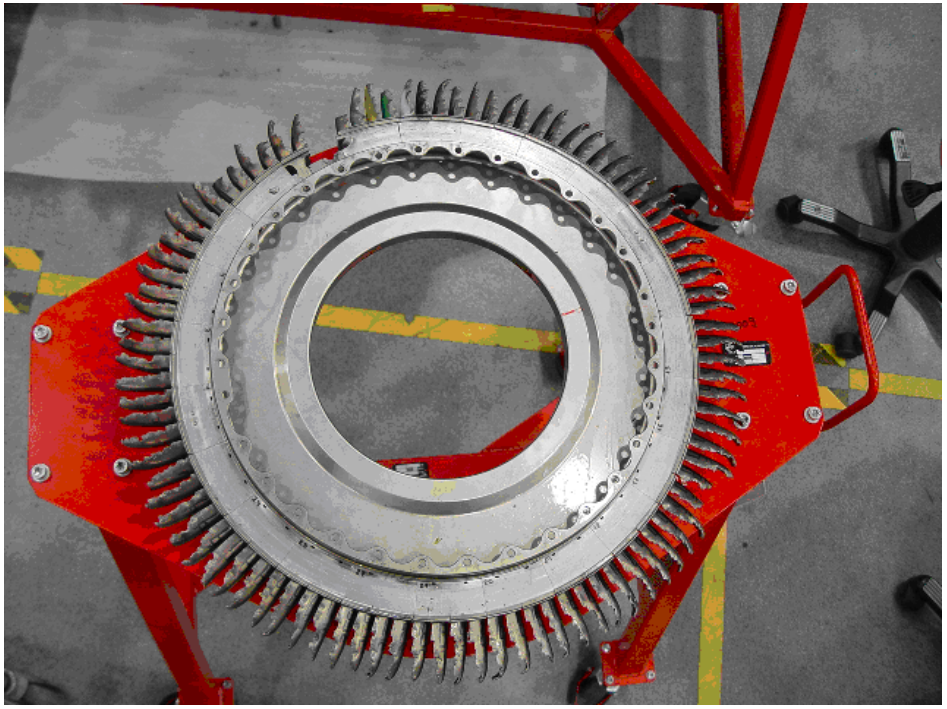
- The JC softening model is not capable to reproduce the experimental results of ballistic tests when plates are at high temperature for this material.
- A new model, as a modification of the JC model, is proposed using a melt extended temperature. JCT.
- The model has been implemented in LS-DYNA code.
- The simulations show that the proposed model JCT is able to reproduce the ballistic behavior of the material studied.
- Current work of turbine engine containment is now possible using this model, and it is currently under investigation.

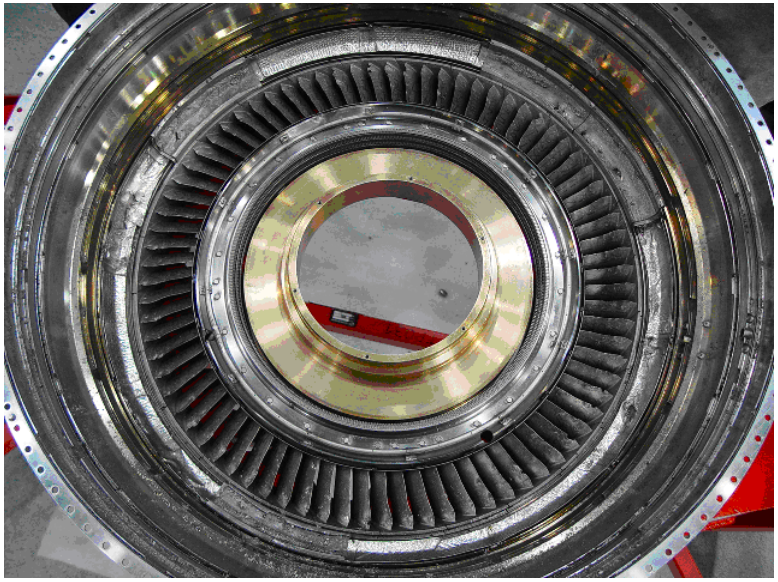
The authors would like to acknowledge ITP for its financial support.

Containment test

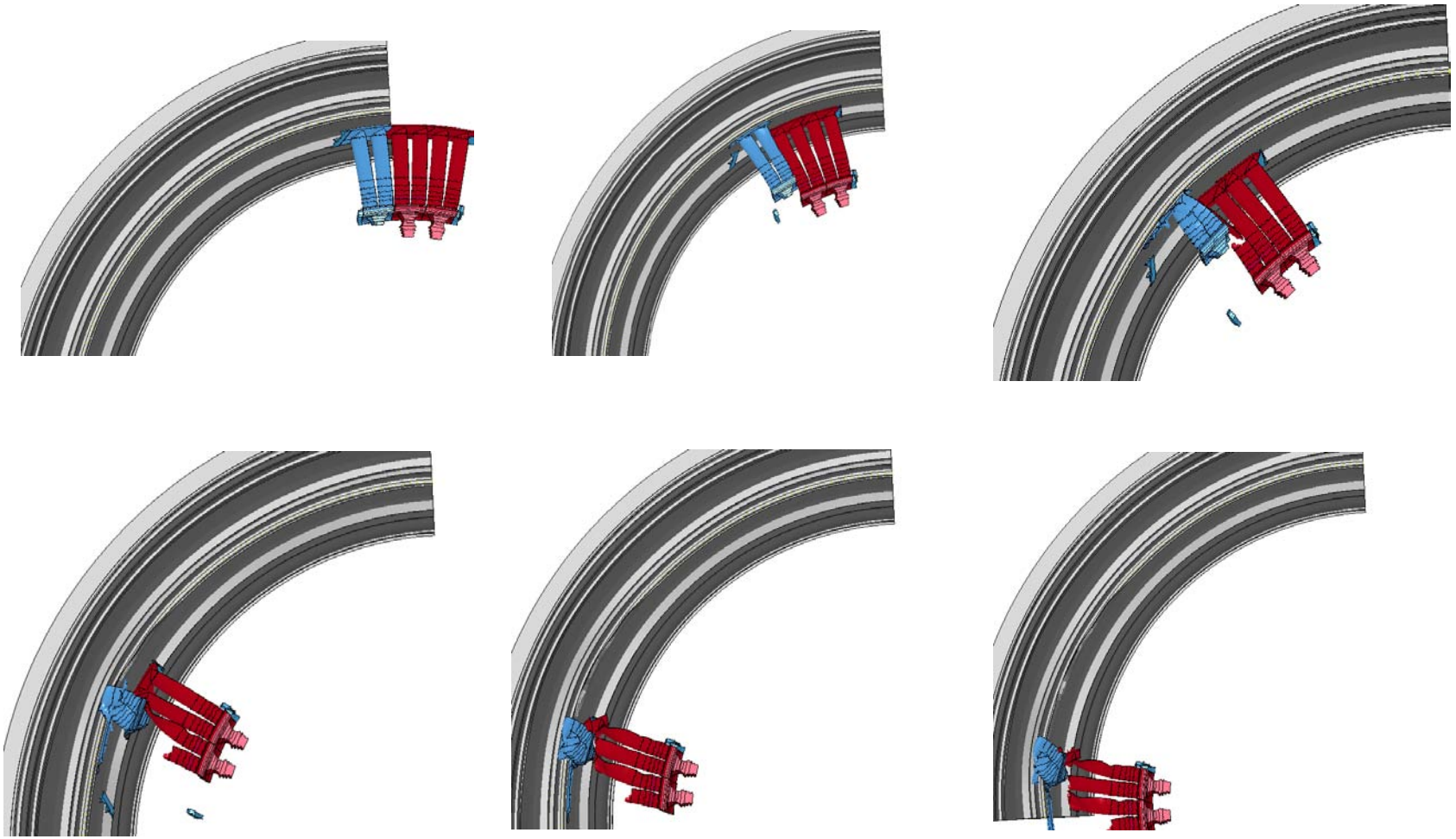


Containment test





Containment test



Containment test